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Exploring the integration of bioelectrochemical systems and hydroponics: Possibilities, challenges, and innovations

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Highlights

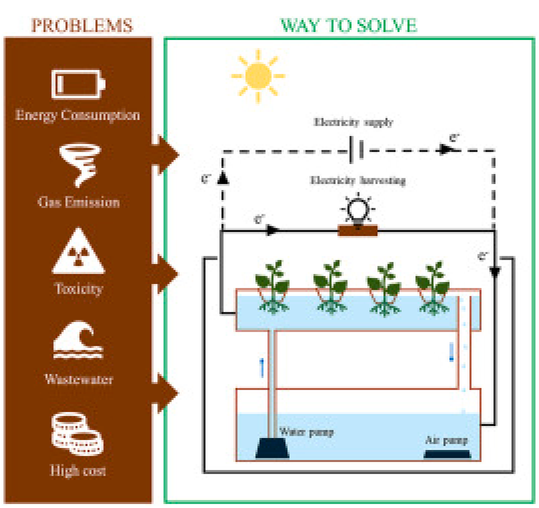
- Major obstacles impeded the sustainable development of hydroponics were summarized.
- The integration of bioelectrochemical systems (BES) and hydroponics was explored.
- Novel configurations of bioelectrochemical-hydroponic systems were postulated.

- Further works on the suitability of BES-hydroponic systems were addressed.

Abstract

Hydroponics is a modern cultivation technique that utilizes nutrient solutions instead of soil for crop production. Currently, challenges, such as high cost, high energy consumption, greenhouse gas emission, and significant wastewater generation are drawbacks that limit its scale up. On the other hand, bioelectrochemical systems have emerged as a sustainable technology that resolve some of the aforementioned drawbacks, albeit in other scenarios. Bioelectrochemical systems applications are well documented in desalination, metal recovery, energy generation, contamination remediation etc. This work conceptualizes the integration of bioelectrochemical systems and hydroponics with a view to improving the efficiency and sustainability of hydroponics. Firstly, a systematic review of the main challenges hindering hydroponic agriculture development is first carried out to identify possible entry points for the proposed systems integration. Thereafter, a conceptualized point-by-point resolution of the main identified challenges of hydroponic systems through bioelectrochemical systems integration is explored. Furthermore, the feasibility, stability, and scalability of the conceptualized hydroponic-bioelectrochemical integrated systems are discussed.

Graphical abstract



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Introduction

The growth rate of the global human population is 1.1% or around 83 million annually (Nations, 2017), making the optimization of land area and the conservation of biodiversity more challenging. According to FAO (Bruinsma, 2003), a projected net increase in the arable area of 120 million ha (12%) will happen in developing countries by 2030 (from 956 to 1076 million ha). With more water, food, and living habitat needed for agricultural cultivation, emerging environmental problems including forest loss, greenhouse gas emissions, and climate change implications are to be expected (Ramankutty et al., 2018). Besides problems for human health, agriculture and decreasing crop yields are also to be expected to be affected (Kinnunen et al., 2020; Rohr et al., 2019). Soil, the most favorable and available support matrix in agriculture will be particularly affected due to increased erosion, compaction, degradation, leading to a decline of topographical conditions, etc., all causing limiting agricultural productivity.

In recent times, hydroponic agriculture has gained popularity as the promise of growing terrestrial plants by solely exposing their roots exposed to a nutritious liquid removes the reliance on the soil as a growing medium (dos Santos et al., 2013). It is an environmentally sustainable way to address the water and soil scarcity, improve the productivity of various crops species and help to face the challenges of climate change (Shafeena, 2016; Sardare and Admane, 2013) Nutrients used in hydroponic systems come from a wide range of sources, such as manure, chemical fertilizers, wastewater, artificial nutrient solutions, etc. (Jones Jr, 2016). According to Barbosa et al. (2015), the land requirements of the hydroponic systems can be ten times less and the yields can be over 11 times greater than traditional agriculture. In addition, when compared with soil cultivation (0.23 kg carbon dioxide (CO_2) equivalent), hydroponic systems have low gas emissions (0.11 kg CO_2 equivalent) (Martinez-Mate et al., 2018). It also has significant potential to save water as water is recycled in hydroponic set originalups (Kumar and Cho, 2014), and as much as 33% of water was recycled in a hydroponic system used for tomatoes (Grewal et al., 2011). Other advantages of hydroponic cultivation systems include that they can be grown in urban areas, are not limited by season, efficiently use fertilizers, and the whole cultivation can be controlled (Hussain et al., 2014; Liu et al., 2012; Modu et al., 2020).

The productivity and quality of hydroponic system crops are markedly dependent on the nutrients acquired from the growing solution (Valentinuzzi et al., 2015). It is interesting to note that the root physiological process is affected by both the availability levels of the nutrients in the medium solution and the interactions among the different nutrients (Sambo et al., 2019). Besides, temperature, pH, allelopathy/autotoxicity phenomenon, etc. all have a huge influence on hydroponic systems. Environmental temperature monitoring, plant health, high initial cost, gas production, high energy consumption, a huge amount of water needed as the solvent, discharge of nutrition wastewater treatment, more quickly speed of disease in solution, etc. are the main challenges associated with hydroponic systems.

Bioelectrochemical systems (BESs) are a group of biotechnologies, which exploit the activities of microorganisms or enzymes to convert chemical energy from waste (e.g. wastewater, polluted soil, sediment, etc.) into sustainable bioelectricity, fuels, or generation of useable by-products (Hoang et al., 2022; Zhang et al., 2019). The major types of BES include microbial fuel cell (MFC), microbial desalination cell (MDC), microbial electrosynthesis cell (MES), enzymatic biofuel cell (EBC), microbial reverse-electrodialysis cell (MRC), microbial solar cell (MSC), and microbial electrolysis cell (MEC) (Ivase et al., 2020). BESs can also be integrated with advanced technologies such as photocatalysts to produce hydrogen (Patil et al., 2019), or photobioreactors to convert hydrogen to more clean energy and pure water (Sirohi et al., 2022). BESs are used mostly for renewable power generation, wastewater treatment, biosensors, nutrients recovery/removal, etc. (Hadiyanto et al., 2022; Kumar et al., 2018b; Li et al., 2018). In 2008, this technology was first merged with plants to form a hybrid system consisting of biocontrol and bio-process structures, mainly involving the conversion of excess organic matter into bioelectricity by microbes living around the rhizosphere region of the plant (Schamphelaire et al., 2008). As autotrophs, plants use solar energy to produce biomass with the help of chlorophyll; while 40% of the biomass will be consumed by itself, the remaining part will be exuded to the rhizosphere region (Strik et al., 2008). The promising nature of these plants combined with BES means that besides electricity generation, they can also be easily integrated into the existing indoor-based agricultural system without competition with plants (Nitisoravut and Regmi, 2017).

For a period of 5 years (2017–2022), about 668 review articles (Scopus data) reviewed the different aspects of BESs, including wastewater treatment (Al-Sahari et al., 2021; Cecconet et al., 2020; Yan et al., 2019), valuable products recovery (Das et al., 2019; Zou and He, 2018), fundamental principles and mechanisms (Gul and Ahmad, 2019; Ivase et al., 2020; Logan et al., 2019), mathematical models for BESs (Gadkari et al., 2018), environmental remediation (Fernando et al., 2019; Wang et al., 2021) and valuable chemical synthesis (e.g., CO, H_2O_2, etc.) (Barbosa et al., 2021; Q. Zhao et al., 2021). In addition, some of the previous review articles have outlined the combination of BES with plants and constructed wetland (CWL). For example, Kabutey et al. (2019) comprehensively reviewed the fundamental aspects of PMFCs in terms of living plants, supporting matrix, rhizosphere microorganisms, mechanism of substrate conversion, and electron transfer. Maddalwar et al. (2021) presented an extensive review of the challenges and commercially feasible associated with PMFC, various factors (e.g., carbon dioxide concentration in air, light intensity, electrode materials, type of plants, etc.), and the possibility of future intervention (e.g., application of biochar and preferable plants). Apollon et al. (2021) provided the recent configuration development of PMFC and evaluated the performance of PMFC in different water conditions (including power density, the requirements to generate bioelectricity, as well the bioelectricity measurements and calculations). Wang et al. (2020) summarized the wastewater treatment and electricity production mechanism of various CWL-MFCs in terms of microorganisms, electrodes, substrates, and wetland plants. As can be seen, most of the previous review articles are largely focused on the development of BES technologies, the application in industry, or the principle and mechanism of PMFC. As mentioned above, although hydroponics is very important for agricultural production, as far as we know, there is no detailed exploration and discussion of the potential applications of BES for specific problems in hydroponic agriculture. Therefore, different from the exist review papers, our work not only limit to the development of hydroponic agriculture and BES, but also proposed the concept of BES-hydroponic systems.

This article explores the potential for the usage of renewable sustainable BES for resolving several problems with hydroponic agriculture. To date, only one study attempted to combine both systems for domestic wastewater treatment and chemical removal, achieving 72±2.4% COD, 83±1.1% phosphate, 35±4.2% ammonia removal efficiencies, and the maximum power density of 31.9 mW/m^2 (Yadav et al., 2020). However, no study has focused on the development of BES or its potential in the hydroponic research field. In this work, we first present an overview of hydroponic agriculture cultivation with the help of bibliometric analysis. Thereafter, we conceptualize how problems identified with traditional hydroponic system cultivation can be solved with BES. The possible characteristics, advantages, and disadvantages of BES in hydroponic systems were also discussed. Based on the in-depth study and analysis of BESs in hydroponic systems, the main problems of BES-hydroponic systems such as the lack of in-depth discussion and mechanism between BESs and hydroponic systems, the monitoring obstacle of the chemicals in hydroponic systems, the risk of over-complicate systems, etc. were reviewed. Various solutions in BES-hydroponic systems include optimizing BES-hydroponic systems, focusing on the mechanism between BES and plant growth, exploring the model systems and more advanced BES systems, as well as the utilizing of decision tree were proposed.

The rest of the paper is structured as follows: Section 2 addresses the problems in hydroponic systems. Section 3 proposes the concept, configuration, and problems advantages of BES-hydroponic systems. Section 4 analysis the influencing factors, economic analysis, and environmental impact of BES-hydroponic systems. Section 5 discusses the limitations and presents the potential development direction of BES-hydroponic systems. Section 6 conclude this paper.

Section snippets

Hydroponic systems

Hydroponic also called soilless cultivation, is a system supplying plants with nutrients (water and minerals) with or without growing medium (e.g., clay, rocks, peat moss, etc.) (Goddek et al., 2019; Kozai, 2018). The term 'Hydroponic' literal translation means water work, which was derived from two Greek words, '*hydro*' and '*ponos*' meaning water and labor, respectively (Sharma et al., 2018). The timeline of hydroponic agriculture development is shown in Fig. 1(a). There are three main culture…

Bioelectrochemical systems

Bioelectrochemical systems (BESs) also called microbial electrochemical systems, convert chemical energy into electrical energy by employing microbes as catalysts. BES has been employed in various ways (biosensing, renewable energy production, wastewater treatment, nutrients recovery, etc.) to achieve many goals. Specifically, the common types include: MFC, generating electrical energy via degrading organic matters (Santoro et al., 2017); MDC, providing desalinated water from seawater/brackish…

Techno-economic analysis

One main advantage of BESs combined with hydroponic systems is their capability to directly extract electric energy from the hydroponic substrate. Unlike the traditional power, electricity generates from BESs is a cleaner and more widely useable form of energy. Besides, BESs can run well at a wide temperature range (Larrosa-Guerrero et al., 2010), therefore, they are more flexible in the hydroponic system. From the environmental sustainability of the hydroponic agricultural point of view, the…

Further perspective

Hydroponic agriculture has the potential to supplement agriculture in many areas worldwide (Sardare and Admane, 2013), and thinking forward on challenges that may thwart its sustainability is paramount. As shown in Table 4, the selection of proper BESs is very important, which relies on several factors and main problems. Under the synergy of BES innovations, the main problems of hydroponics could be solved. The integration proposed in this paper needs further consideration if commercial-scale…

Conclusion

This paper explores an important concept relating to the integration of BES with hydroponic systems in order to make the latter more sustainable. Although hydroponic systems have a huge potential, it is still plagued by problems such as high cost, high energy consumption, greenhouse gas emission, nutrition solution, wastewater discharge, etc. We have discussed the possibilities for alleviation of these problems through BES, which can be a valid pathway for reducing greenhouse gas emissions (at…

CRediT authorship contribution statement

Shuyao Wang: Conceptualization, Methodology, Data curation, Investigation, Writing – original draft. **Ademola Adekunle:** Writing – review & editing, Conceptualization, Methodology. **Vijaya Raghavan:** Writing – review & editing.…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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